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The role of land use change in the recent warming of daily extreme temperatures

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[1] Understanding how temperature extremes respond in a climate forced by human activity is of great importance, as extreme temperatures are detrimental to health and often responsible for mortality increases. While previous detection and attribution studies demonstrated a significant human influence on the recent warming of daily extremes, contributions of individual anthropogenic forcings like changes in land use have not yet been investigated in such studies. Here we apply an optimal fingerprinting technique to data from observations and experiments with a new earth system model to examine whether changing land use has led to detectable changes in daily extreme temperatures on a quasi-global scale. We find that loss of trees and increase of grassland since preindustrial times has caused an overall cooling trend in both mean and extreme temperatures which is detectable in the observed changes of warm but not cold extremes. The warming in both mean and extreme temperatures due to anthropogenic forcings other than land use is detected in all cases, whereas the weaker effect of natural climatic forcings is not detected in any. This is the first formal attribution of observed climatic changes to changing land use, suggesting further investigations are justified, particularly in studies of warm extremes. **Citation:** Christidis, N., P. A. Stott, G. C. Hegerl, and R. A. Betts (2013), The role of land use change in the recent warming of daily extreme temperatures, *Geophys. Res. Lett.*, 40, 589–594, doi:10.1002/grl.50159.

1. Introduction

[2] The impact of changing land use on regional climates has been demonstrated in both observational and model studies [Findell *et al.*, 2007; Pielke *et al.*, 2011]. The climatic impact is multifaceted and determined by the interplay of several factors, including radiative effects through albedo changes [Myhre *et al.*, 2005], hydrological effects through root and stomatal properties and changes in evapotranspiration that affect surface heat and sensible fluxes [Davin and de Noblet-Ducoudré, 2010], and biogeochemical influences through altered CO₂ emission or uptake [Betts, 2000; Betts *et al.*, 2007]. These effects can lead to opposite responses, which may also vary considerably with location. Although the sign of the global mean radiative forcing from albedo changes has a small and negative value of $-0.2 \pm 0.2 \text{ W m}^{-2}$

[Forster *et al.*, 2007] indicative of a cooling, the contribution of all other effects may change the sign of the response [Pongratz *et al.*, 2010]. Larger forcings due to emissions of greenhouse gases and aerosols diminish the impact of land use changes (henceforth referred to as LU) on the global mean temperature, and therefore, LU is often absent in general circulation model (GCM) simulations of the postindustrial climate. On the other hand, there is strong evidence that the regional climatic effects of LU can be as important as that of the globally bigger forcings [Zhao and Pitman, 2002; Findell *et al.*, 2007]. Moreover, it has been suggested that the LU effect may be more prominent in extreme temperatures and especially warm extremes [Voldoire and Royer, 2004]. Portman *et al.* [2009] suggest that changing vegetation may have affected extremes in the United States through changes in aerosols. Teuling *et al.* [2010] find that less severe heat waves are expected in forested areas in Europe as opposed to grasslands, and Pitman *et al.* [2012a] show that in several regions, the impact of the LU forcing on extremes is comparable to that of a doubling in CO₂ with repercussions for detection and attribution studies.

[3] Identifying causes of change in temperature extremes is of great interest to both the public and decision makers, as extremes are often associated with adverse socioeconomic impacts. While detection and attribution studies have shown a significant anthropogenic role in the warming of daily temperature extremes in recent decades [Christidis *et al.*, 2011; Zwiers *et al.*, 2011; Morak *et al.*, 2012], a further partitioning of the anthropogenic response between individual components like LU has not yet been attempted. Here we make use of observational and GCM daily maximum and minimum temperature (Tmax and Tmin) data and carry out the first formal detection and attribution analysis that employs optimal fingerprinting [Allen and Stott, 2003] to examine whether the LU effect can be detected in recent observed changes in warm and cold daily extremes on a global scale. We contrast the detectability of the LU signal between extreme and mean temperatures and investigate whether omitting the LU forcing in GCM simulations could be a disadvantage in studies of extremes.

2. Data

[4] We examine changes in the warmest day (WD), warmest night (WN), coldest day (CD), and coldest night (CN) of the year during 1951–2003. The indices are taken from HadEX [Alexander *et al.*, 2006], a global land-based $2.5^\circ \times 3.75^\circ$ gridded observational dataset, and are the local estimates at grid points with available data. The indices are also computed using daily Tmax and Tmin data from experiments with the new Hadley Centre Earth System model HadGEM2-ES [Jones *et al.*, 2011] run at N96 resolution. We use data from two experiments: the first (ALL) simulates the effect of all major anthropogenic and natural external forcings. These include historical changes in well-mixed greenhouse gases, sulphate aerosols, ozone, black carbon, biomass burning

All Supporting Information may be found in the online version of this article.

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aerosols, and changing land use, as well as natural forcings associated with changes in the solar output and volcanic aerosols. The second experiment (LU) includes only the LU effect. In the experiments that include LU, the model simulates biophysical effects and also prescribes CO₂ emissions from land use change [Jones *et al.*, 2011]. Assuming a linear combination of the climatic response to different forcings, the difference between the responses simulated by the two experiments (ALL-LU) approximates the effect of all forcings but without the changes in land use. A third experiment that includes the natural forcings only (NAT) is also used in the fingerprinting analysis. Each experiment is an ensemble of four simulations which start from well-separated points of a long control simulation without any external forcings. Finally, we use 1000 years of the control simulation to model the effect of internal climate variability.

[5] Unlike previous Hadley Centre models which used prescribed changes in land cover or vegetation types, in HadGEM2-ES simulations, we combine a dynamic global vegetation model [Cox, 2001] with an imposed time-varying agricultural disturbance from Hurtt *et al.* [2011]. The disturbance represents the coverage of managed land in which only grass types are allowed to grow. The total grass-cover fraction considered in this study includes both natural grasses and crops. Figure 1 shows the change in the tree- and grass-cover fraction since preindustrial times, corresponding to the ensemble mean of the four ALL simulations. The fractions, estimated with the vegetation model from the response to the anthropogenic disturbance, are found to be very similar in all simulations that include the LU effect. The historical decrease in tree-cover and increase in grassland is the dominant feature of the land surface modification. According to the model, between the 1860s and the 2000s, the global mean tree fraction has decreased by 0.034, whereas the grass fraction has increased by 0.057. We next examine how these changes have affected extreme daily temperatures.

[6] Figure 2 illustrates time series of the four extreme indices (WD, WN, CD, and CN) averaged over the quasi-global area where observations are available. Time series of the annual mean temperature are also shown for comparison. The observed annual mean temperatures are computed from the CRUTEM3 dataset [Brohan *et al.*, 2006]. Model-based time series corresponding to the ensemble mean of the ALL and LU experiments and their difference (ALL-LU) are also plotted. The model data are regridded on the observational grid and masked to have the same coverage with the observations before the area means are computed. Figure 2 shows that the observed warming in cold extremes in recent years ($\sim 2\text{K}$) is about twice as much as the warming in warm extremes and in the annual mean ($\sim 1\text{K}$), a known asymmetry in the change of the temperature distribution [Morak *et al.*, 2012]. Cold extremes also display a higher year-to-year variability. The ALL time series agree best with the observations in the case of the WD index but show a smaller warming trend in the CD and CN time series. The LU trend is negative in all cases and has a greater effect in the WD time series, where the exclusion of LU in the simulations with all forcings would double the trend. The LU cooling persists throughout the period shown in Figure 2, and the associated temperature anomalies tend to be positive before and negative after the 1961–1990 base

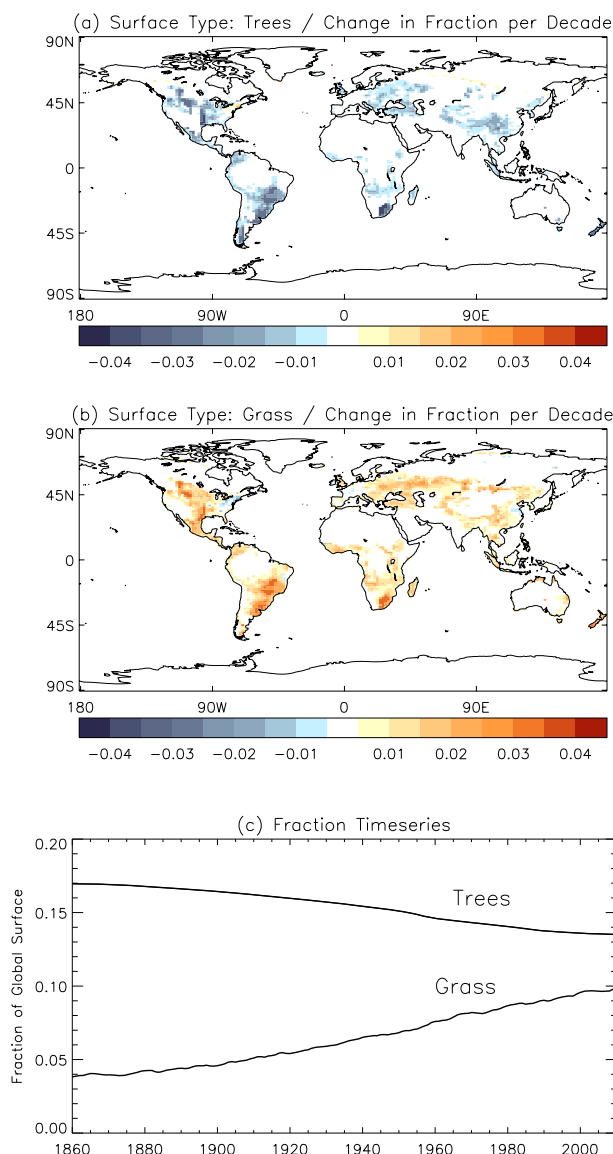


Figure 1. Patterns of the 1860–2010 trend in (a) the tree-cover fraction and (b) the grass-cover fraction. (c) Time series of the global mean tree and grass fraction. The fractions are estimated from the ensemble mean of the four model simulations with ALL forcings.

period. The observed warming in the early part of the WD time series seems to be linked to the LU effect (positive temperature anomalies before the base period), whereas the warming in recent years is consistent with the effect of all other forcings, while both warming periods are significant at the 10% level as they lie above the gray horizontal lines in Figure 2a. The same seems to be the case for WN, although the warming in the early 1950s is less pronounced. Inclusion of the LU effect, however, seems to have no noticeable impact in the global mean values of the cold indices and the annual mean temperature, although of course this may not necessarily be the case at regional scales.

[7] The LU effect is likely to be more detectable in the changes of warm day extremes, given there is less cooling from LU in night time and cold day extremes (Figure 2). Boisier *et al.* [2012] showed that in temperate regions,

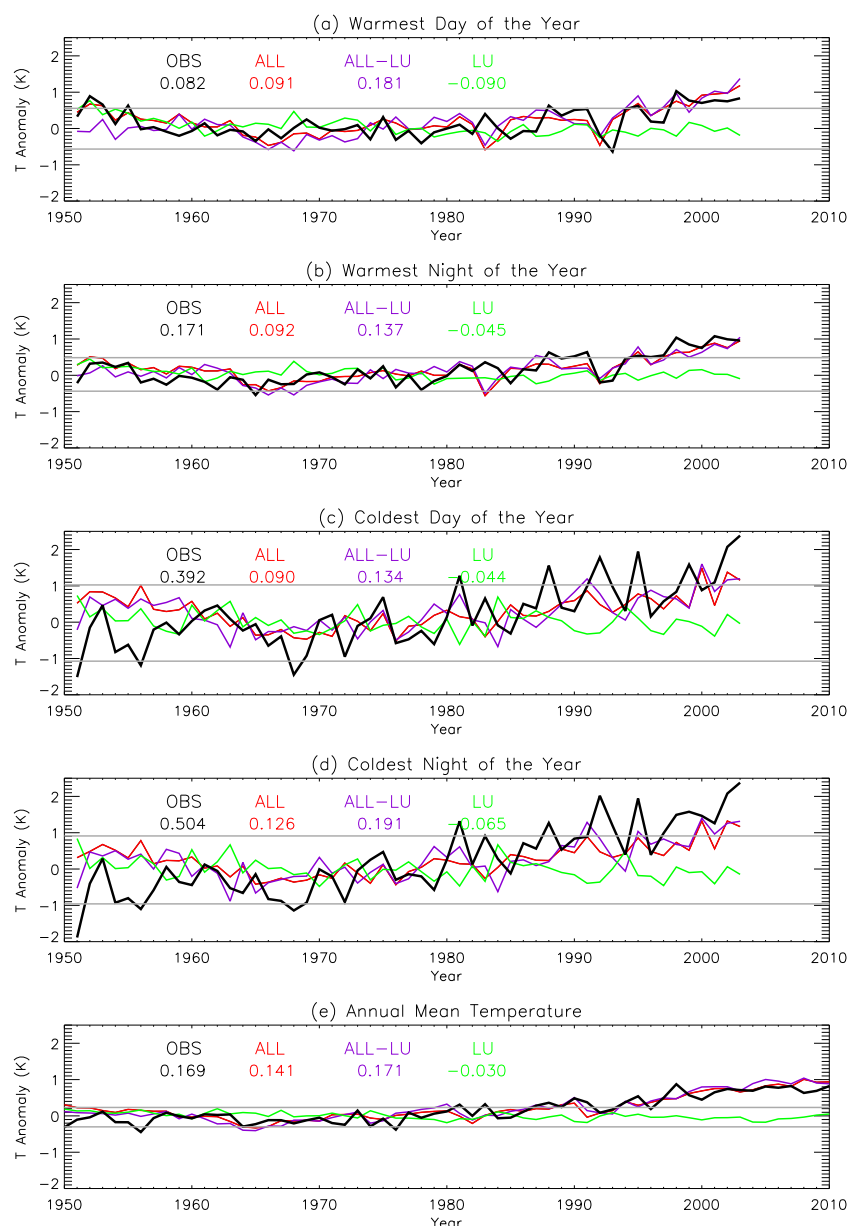


Figure 2. Time series of the global mean (a–d) extreme temperature indices and (e) annual mean temperature (plotted as anomalies relative to the 1961–1990 mean) corresponding to the observations (thick black line) and the ensemble mean of experiments with ALL forcings (red line), the LU forcing (green), and their difference ALL-LU (purple). The estimated trends over the plotted period are also marked on each panel (in units of K/decade). The gray horizontal lines mark the 5%–95% range of internal variability estimated using order statistics from segments of equal length to the observations extracted from the control simulation. The model data are in all cases masked to have the same coverage as the observations.

changes in the total turbulent energy flux associated with LU lead to a warming, which to some extent counteracts the cooling from albedo changes. Solar insolation (required both for the albedo effect and also to drive turbulent fluxes that could change the partitioning of the available energy at the surface) is reduced during cold days and absent in night time. It is therefore expected that LU will have most influence on warm day extremes, as also confirmed by the stronger cooling trends found with our model experiments.

[8] The 1951–2003 patterns of the WD trend are mapped in Figure 3. We highlight the WD index, as the LU effect appears to be most prominent in warm day extremes. Both

the HadEX and the ALL patterns show areas of both warming and cooling in Eurasia and North America, while in the absence of LU (Figure 3c), the trend patterns feature a more widespread warming. Internal variability has a greater effect at smaller scales and may be responsible for some of the regional differences between the observed and ALL patterns. The overall cooling over land in the LU patterns (Figure 3d) is in contrast with the warming south of the Amazon in a region influenced by the Atlantic Forest deforestation (Figure 1a). The difference can be explained by the dominance of the albedo effect at mid latitudes (i.e. grasslands reflecting more solar radiation than forested

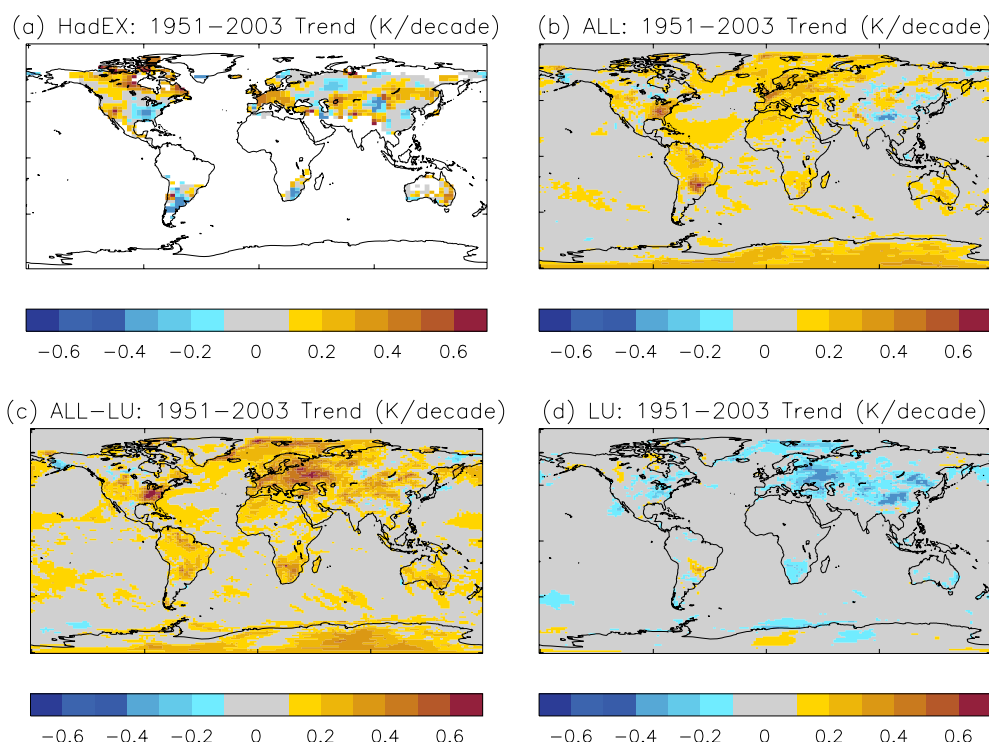


Figure 3. Patterns of the 1951–2003 trend of the WD index for warm days (in K/decade) estimated from (a) the observations and the ensemble mean of model experiments with (b) ALL forcings, (d) the LU forcing, and (c) their difference, ALL-LU.

areas), as opposed to the dominance of the evapotranspiration effect in the tropics (i.e., enhanced heating due to drier soil in deforested areas), as also found in other studies [Davin and de Noblet-Ducoudré, 2010; Lawrence and Chase, 2010].

3. Attribution

[9] We next carry out an optimal fingerprinting analysis [Allen and Stott, 2003] to make a rigorous assessment of the signal detectability. The method has been applied to numerous detection and attribution studies and helped establish the key role of anthropogenic forcings in the recent warming of mean and extreme temperatures at global and regional scales [Hegerl et al., 2007]. Signal detectability is inferred by the scaling factors of a generalized multivariate regression model that partitions the observed change between the climate response to individual forcings, taking into account the effect of internal variability. The components of the response are represented by the ensemble mean of the corresponding model experiments (model fingerprints). Scaling factors significantly different than zero indicate a detectable signal, while factors consistent with unity imply a good match between the model and the observations. Here we attempt to separate the LU response from all other forcings, i.e., estimate scaling factors for the ALL-LU and LU components. We carry out separate analyses for each extreme index and the annual mean temperature. The observational and model data are organized into vectors that comprise 4-year mean values of the index (or the annual mean temperature) at all grid points with available observations in consecutive time-slices during the 52-year period 1952–2003 (i.e., 1952–1955, 1956–1959 ... 1999–2003). The 4-year mean index patterns of each time-slice are spatially smoothed

with spherical harmonics at T4 truncation, a common procedure in attribution studies that aims to increase the signal-to-noise ratio. The model fingerprints are then regressed against the observations using also estimates of the noise that affects both (see electronic supplement).

[10] Scaling factors from two-fingerprint analyses are shown in Figure 4a. The effect of ALL-LU is detected in all cases, and except from the indices associated with cold extremes, the scaling factors have a small uncertainty range. The effect is underestimated by the model for CD and CN (scaling factors significantly greater than unity), consistent with the fact that the ALL-LU trends (Figure 2c and 2d) are considerably smaller than the trends in the observations. The impact of LU is only detectable in the observed changes of warm extremes, and its scaling factor has the smallest uncertainty range in the WD analysis. This is the first time the fingerprint of LU is detected in a formal attribution study. The LU effect is not detectable in the mean temperature analysis, which confirms the common understanding that the LU forcing has little effect on the observed warming on a global scale. LU is also not detected in the analyses of the cold indices, which may be partly due to the higher variability associated with them. We also performed three-fingerprint analyses, which include the NAT ensemble and partition the climate response between the ALL-LU-NAT, LU, and NAT components (Figure 4b). The main effect of the NAT forcing is the cooling following the Pinatubo eruption, evident in the time series of warm extremes (Figures 2a and 2b), but this is not detected in the attribution analysis, possibly due to the 4-year averaging which largely reduces the effect of volcanic eruptions. The ALL-LU-NAT fingerprint is detected in all cases, and the impact of LU is still detectable in analyses of warm extremes.

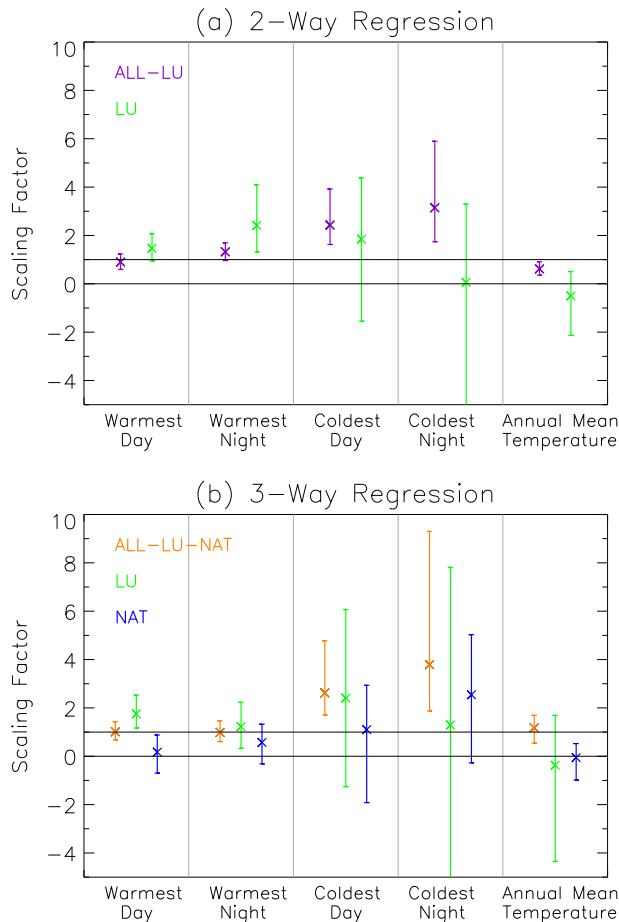


Figure 4. Scaling factors and their 5%–95% uncertainty range from optimal fingerprinting analyses corresponding to the four extreme indices and the annual mean temperature. Results are shown for (a) a two-way regression that decomposes the forced response between the ALL-LU (purple) and LU (green) components and (b) a three-way regression that provides factors for the ALL-LU-NAT (orange), LU (green), and NAT (blue) components. Scaling factors inconsistent with zero indicate a detectable signal.

4. Discussion

[11] Our attribution study with HadGEM2-ES provides the first indication that land use changes have induced a significant cooling in warm extremes of daily temperature on a global scale, which offsets to some degree the warming trend from other anthropogenic forcings. It is therefore essential that LU is accounted for in attribution investigations of changes in extremes. The LU effect is most prominent in some regions like Eurasia and Eastern North America (Figure 3; see also time series in the electronic supplement). In this study, we focus on the global-scale effect of LU, as enhanced internal variability at smaller scales reduces the signal to noise ratio and hence signal detectability. We find that LU has led to a significant large-scale cooling of extremely warm days, consistent with the albedo increase that accompanies deforestation. While the albedo effect is most prominent in the extra-tropics, hydrological changes associated with LU may dominate in tropical regions and lead to a warming of warm day extremes. Moreover, continuing emissions of anthropogenic greenhouse gases are expected to increase

the severity of warm extremes, and depending on the scale of future land cover change, their effect may become increasingly more important relative to the effect of the LU forcing. We find no significant influence from LU on cold extremes and the annual mean temperature.

[12] Differences in the climate response to LU simulated by different models have been highlighted before and have been linked to differences in the model representation of this complex forcing (Pitman *et al.* [2009]; de Noblet-Ducoudré *et al.* [2012]). It is therefore important to confirm our findings with other models in future work. As the existing multimodel studies of LU employ a different experimental design than attribution studies, such a multi-model approach has not been possible yet. It is crucial that earth system models used to investigate the effect of LU employ high-quality data, while future studies could also consider missing processes like irrigation, urbanization, and isoprene emissions. Moreover, regional model studies would help assess local effects [Pitman *et al.*, 2012b] and provide useful information for adaptation planning. Smaller forcings like LU may not have much influence on the change in the global temperature but may play a key role in our understanding of changes in other climatic parameters (like extremes), as well as local climate change.

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